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Review paper

ENERGY EFFICIENCY OF MODERN UNDERGROUND MINE VENTILATION CONTROL STRATEGIES: A CRITICAL REVIEW OF RESEARCH FINDINGS

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Abstract: Underground mine ventilation serves both as a critical safety system and as one of the major consumers of electrical energy in underground mining operations. This paper presents a critical review of the energy performance of ventilation management strategies, focusing on ventilation network optimization, fan speed control, Ventilation-on-Demand (VoD), model-based control, computational fluid dynamics (CFD) applications, and sensor-based monitoring. The review is organized according to the level of intervention and validation, encompassing industrial measurements, pilot-scale and laboratory studies, as well as numerical simulations. The findings indicate that direct energy savings are most commonly achieved through the reduction of network resistance and pressure losses, fan speed adjustment, and the spatial and temporal alignment of airflow distribution with actual operational requirements. CFD analyses and monitoring systems do not constitute energy-saving measures by themselves; rather, they provide the basis for defining safe operating limits and enabling closed-loop control strategies. Reported energy savings are not directly comparable due to differences in baseline operating conditions, system boundaries, and validation methodologies. Reliable implementation requires the maintenance of minimum safety airflow rates, the provision of backup safety measures, and automatic transition to predefined safe operating modes in the event of sensor, communication, or actuator failures.

Keywords: mine ventilation; energy efficiency; Ventilation-on-Demand; variable frequency drive control; validation

1 INTRODUCTION

Ventilation in underground mines ensures the supply of fresh air, the dilution and removal of gases and airborne contaminants, the control of heat and humidity, and the maintenance of environmental conditions required for the safe operation of personnel

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and equipment. At the same time, due to the continuous operation of main and auxiliary ventilation fans, it represents a significant component of the Mine's overall energy consumption (McPherson, 1993; Hartman et al., 1997).

Ventilation systems are commonly designed to satisfy worst-case or peak-demand operating conditions, whereas actual airflow requirements vary with the location of active workings, equipment utilization, contaminant emissions, and the ongoing development of the ventilation network. The mismatch between design conditions and real-time demand frequently results in excessive airflow, throttling losses at regulators, fan operation outside the optimum efficiency range, and unnecessary energy losses in inactive sections of the network. Although designing mine ventilation systems according to maximum anticipated demand is a rational engineering approach, the expansion of underground infrastructure, often driven by exploration and mine development activities, can make the delivery of adequate airflow to all working areas increasingly challenging, particularly when overall energy costs must be minimized.

The use of diesel-powered underground equipment, oxidation of sulphide ores, geological conditions involving carbonate formations, methane, hydrogen, radon, or sulphur-bearing strata, as well as the generation of nitrogen oxides following blasting operations, are only some of the factors contributing to the complexity of underground mine ventilation (Semin et al., 2020; Brake, 2006).

The objective of this paper is to compare contemporary ventilation management strategies with respect to three key questions:

- by which mechanisms they influence energy consumption,
- how their performance has been validated, and
- which safety and infrastructure constraints determine their applicability.

On this basis, the reviewed approaches are classified into direct energy-efficiency interventions targeting ventilation networks and fans, and enabling technologies such as CFD modelling, monitoring systems, and predictive control models.

2 METHODOLOGICAL FRAMEWORK

The analysis encompassed monographs, peer-reviewed journal articles, and conference papers published between 1989 and 2025. Relevant sources were identified using combinations of the following keywords: *mine ventilation, underground mine energy efficiency, ventilation on demand, variable frequency drive, mine ventilation optimization, CFD mine ventilation, and ventilation monitoring*.

The literature selection has been focused on studies addressing underground mine ventilation and presenting a technical intervention, mathematical model, or control strategy, together with either quantified energy performance indicators or a justified assessment of their influence on ventilation system safety.

For each selected source, the level and type of intervention, ventilation system characteristics, validation methodology, reported energy-related outcomes, and identified safety constraints were examined. The results were evaluated according to the method of validation, namely industrial measurements, pilot-scale and laboratory investigations, or numerical and optimization-based analyses. Due to differences in baseline operating conditions, system boundaries, and monitoring periods among the reviewed studies, reported energy-saving values were not aggregated into a single average indicator

3 ENERGY PERFORMANCE INDICATORS AND EVALUATION CRITERIA

The primary objective of mine ventilation is to ensure controlled airflow throughout the underground network. The analysis of mine ventilation systems is fundamentally based on the continuity equation, according to which the volumetric airflow rate through a given cross-section is expressed as (McPherson, 1993; Hartman et al., 1997):

$$Q = A \cdot v \tag{1}$$

Where:

Q - volumetric airflow rate (m^3/s),

A - cross-sectional area (m^2),

v - average air velocity (m/s).

As air flows through underground openings, pressure losses occur due to friction, local resistances, cross-sectional changes, network branching, air leakage, and the presence of equipment. In mine ventilation engineering, this relationship is commonly described using the Atkinson equation, or quadratic airflow law (McPherson, 1993; Acuña and Lowndes, 2014):

$$\Delta p = R \cdot Q^2 \tag{2}$$

Where:

Δp – pressure drop across the airway (Pa),

R – aerodynamic resistance of the airway,

Q – volumetric airflow rate (m³/s).

For the assessment of energy efficiency, fan power demand is of particular importance and may be expressed as (McPherson, 1993; Hartman et al., 1997):

$$P = \frac{Q \cdot \Delta p}{\eta} \tag{3}$$

Where:

P – required fan power (W),

Q – airflow rate (m³/s),

Δp – pressure rise generated or overcome by the fan (Pa),

η – overall efficiency of the fan and drive system.

Nowadays, an energy-performance outcome is considered directly validated when a study reports a measured change in power demand, electrical energy consumption, or operating cost relative to a clearly defined baseline operating condition. Results obtained solely through numerical simulations are classified as estimated values, whereas CFD analyses, monitoring systems, and network calibration procedures are treated as enabling tools unless they are integrated with active control measures and validated through field implementation.

4 BASELINE OPERATING CONDITIONS AND SOURCES OF ENERGY LOSSES

In many underground mines, the baseline ventilation configuration consists of fans operating at approximately constant speed, while airflow distribution is controlled through regulators and ventilation doors. Such systems are generally robust and straightforward to operate; however, they are often designed for peak-demand conditions and therefore do not adequately respond to short-term variations in production activity (Jovičić, 1989; Lilić et al., 2000).

Energy losses are not confined to the fan itself. The total power demand of a ventilation system is influenced by airway resistance, air leakage, abrupt changes in airflow direction, poorly designed intake and return airways, throttling losses, and fan operation away from the optimum efficiency point. Consequently, improving a single component does not necessarily lead to improved performance of the overall system.

Papar et al. (1999) describe this challenge as the need for a systems-based approach in which the power supply, motor, drive system, fan, control devices, and ventilation airways are considered as an integrated whole. In the mine investigated by these authors, aerodynamic redesign of intake and discharge components enabled the required airflow to be achieved without installing higher-capacity fans.

This baseline framework is essential for interpreting reported energy savings. Reductions in energy consumption may result from lower airflow requirements, reduced network resistance, improved fan efficiency, or decreased operating time. Meaningful comparison between studies is therefore possible only when the underlying energy-saving mechanism is clearly identified.

5 ENERGY-EFFICIENT MINE VENTILATION MANAGEMENT

5.1 Ventilation Network Optimization

Ventilation network optimization encompasses the reduction of aerodynamic resistance, improvement of airflow distribution, selection of regulator settings, and coordination of multiple fan systems. Energy savings are achieved when the required airflow is delivered with a lower overall pressure drop or when airflow is redistributed from inactive to active sections of the mine without increasing total airflow demand (Acuña and Lowndes, 2014).

Network simulation models provide an efficient means of evaluating alternative operating scenarios; however, the resulting energy savings remain potential benefits until validated through measurements of airflow, pressure, and power consumption. A major limitation is the sensitivity of optimization results to uncertainties in airway resistance and leakage estimates. For this reason, network calibration should precede the implementation of any control strategy.

5.2 Fan and Drive Control

Variable Frequency Drive (VFD) technology enables fan speed to be adjusted according to actual airflow requirements, rather than dissipating excess pressure through throttling devices. Because fan power demand is approximately proportional to the cube of rotational speed, the greatest savings potential exists in systems operating for extended periods under partial-load conditions.

Using a model-based analysis of an auxiliary ventilation system, Gonen (2021) estimated annual energy savings of approximately 53%. However, such results are highly dependent on the operating profile, minimum permissible airflow rates, and assumptions regarding baseline energy consumption.

Field investigations reported by Papar et al. (1999) demonstrate that speed control is not the only available intervention. By modifying the aerodynamic configuration of the ventilation system, existing fans were able to deliver the required design airflow, thereby avoiding the installation of additional fan capacity exceeding 224 kW. This case highlights that VFD implementation should follow a thorough assessment of system sizing, airway configuration, leakage conditions, and fan operating points.

5.3 Ventilation-on-Demand and Model-Based Control

Ventilation-on-Demand (VoD) systems adjust airflow according to the location and timing of actual ventilation requirements. Control signals may be derived from production schedules, operational events, personnel and equipment tracking systems, or measurements of mine atmospheric conditions. Energy benefits are achieved only when monitoring information is translated into adjustments of fan speed, regulator settings, or the operating status of individual ventilation branches. Based on industrial case studies from multiple mines, Costa and da Silva (2020) reported annual energy savings ranging from approximately 21% to 30% following the implementation of different combinations of VoD and VFD technologies. These values should not be interpreted as a universal efficiency indicator, since the mines differed substantially with respect to depth, reliance on auxiliary ventilation, degree of automation, and baseline operating conditions.

Model-based control extends the VoD concept by simultaneously determining optimal operating points for fans and regulators. Sjöström et al. (2020) implemented model-based control of main and booster fans at the Garpenberg Mine and reported an approximately 40% reduction in ventilation energy consumption over a ten-month monitoring period, while continuously tracking airflow and differential pressure throughout the network.

Chatterjee et al. (2015) further demonstrated that optimization strategies can incorporate time-varying electricity tariffs. In such cases, a distinction must be made between reductions in energy consumption and reductions in operating cost, as these objectives are not necessarily equivalent.

The reliability of VoD systems depends on measurement quality and network response characteristics. Ihsan et al. (2024) developed Adaptive Neuro-Fuzzy Inference System (ANFIS) models for predicting optimal fan power requirements and hazardous gas dilution times. Although the models demonstrated promising performance, validation was conducted under laboratory-scale conditions. Consequently, the results confirm methodological feasibility rather than proven energy savings in full-scale mining operations.

5.4 CFD Modelling as a Tool for Defining Safe Operating Limits

Computational Fluid Dynamics (CFD) comprises a set of numerical methods used to simulate velocity, pressure, temperature, and contaminant concentration fields within complex underground geometries. In the context of energy efficiency, its contribution is indirect: CFD can identify airflow recirculation, stagnant zones, inefficient mixing, and localized leakage pathways, but the simulation itself does not reduce energy consumption (Lilić et al., 2000; Yi et al., 2022).

Cheng et al. (2016) applied CFD modelling to optimize methane control while simultaneously preventing spontaneous combustion in a longwall mining environment. Their results demonstrated that increasing airflow rates could effectively reduce methane concentrations; however, higher airflow also increased oxygen ingress into the goaf area, thereby elevating the risk of spontaneous heating. Consequently, the recommended airflow range represented a safety compromise rather than an energy-optimization outcome in a strict sense.

The review research of Brodny and Tutak (2021) and Yi et al. (2022) indicate that CFD is particularly valuable for the design and assessment of auxiliary ventilation systems, smoke and gas dispersion analyses, dust transport studies, and thermal environment evaluations. Its contribution to energy efficiency becomes measurable only when CFD-derived solutions are incorporated into operational control strategies and subsequently validated against baseline operating conditions.

Because CFD results are highly sensitive to geometric representation, boundary conditions turbulence models, and numerical mesh quality, simulation outcomes should always be verified through field measurements before implementation.

5.5 Sensor-Based Monitoring, Network Calibration, and Control Reliability

Monitoring airflow rates, pressure, gas concentrations, temperature, and equipment location constitutes the foundation of a closed-loop ventilation control system. Sensor data enable verification that required airflow quantities are being delivered, facilitate early detection of abnormal operating conditions, and support continuous updating of ventilation network models (Shriwas and Pritchard, 2020).

Continuous airflow monitoring can significantly improve network-model calibration and reduce discrepancies between simulated and actual operating conditions (Zhou et al., 2022). Accurate calibration is particularly important in mines where network resistance changes continuously due to development activities, production advances, and modifications of ventilation infrastructure. Monitoring itself does not generate energy savings; rather, it serves as a prerequisite for reliable ventilation management. Robust systems should incorporate redundant measurement and control channels, signal validation procedures, clearly defined alarm thresholds, and provisions for manual operator intervention.

In the event of communication failure, sensor malfunction, or unreliable measurements, the control system should automatically revert to a predefined safe operating mode, even when such operation results in higher energy consumption Table 1 summarizes studies reporting quantified energy-performance outcomes, whereas Table 2 highlights methods whose primary contribution lies in modelling, validation, or safety enhancement. This distinction prevents simulation-based potential from being interpreted as industrially verified energy savings.

Table 1 Studies Reporting Quantified Energy Performance

Source	Intervention	Validation Method	Energy Outcome
Costa and da Silva (2020)	VoD/VFD implementation in multiple mines	Industrial case studies	21–30% reported annual energy savings
Gonen (2021)	VFD control of auxiliary fans	Model-based analysis	53% estimated annual energy savings
Papar et al. (1999)	Aerodynamic system redesign	Field measurements	Avoided installation of >224 kW additional fan capacity
Sjöström et al. (2020)	Model-based ventilation control	Ten-month industrial monitoring campaign	Approximately 40% reduction in energy consumption
Saleem (2025)	Mathematical and machine-learning model	Numerical analysis	31.24% modelled reduction in energy consumption

Table 2 Enabling Technologies without directly verified Mine-Scale energy savings

Source	Tool/Method	Validation Approach	Contribution to Energy Optimization
Cheng et al. (2016)	CFD modelling	Numerical simulation of a real mine geometry	Determination of safe airflow operating ranges
Ihsan et al. (2024)	ANFIS-based VoD model	Laboratory-scale validation	Prediction of fan power requirements and gas dilution times
Shriwas and Pritchard (2020)	Monitoring and control systems	Review of industrial practice	Foundation for closed-loop ventilation control
Zhou et al. (2022)	Continuous network calibration	Experimental study	Improved reliability and accuracy of network models

Note: Reported energy-saving percentages are not directly comparable because of differences in system boundaries, baseline operating conditions, and calculation methodologies.

The reviewed studies indicate that the largest reported energy savings are generally achieved through the adjustment of fan operation to actual ventilation requirements, primarily by means of VFD control and VoD strategies. In contrast, ventilation network optimization often yields less immediately measurable but potentially more sustainable long-term improvements.

6 DISCUSSION

The results of this review demonstrate that substantial energy savings are rarely achieved through a single intervention. Instead, the greatest benefits arise from the integration of multiple complementary measures. Ventilation network optimization reduces unnecessary pressure losses, VFD control enables fan operation to match airflow demand, and VoD systems direct airflow to locations where mining activities are taking place. Monitoring systems and predictive models provide the information required to determine when and to what extent airflow rates can be safely adjusted.

The applicability of these approaches depends strongly on site-specific mining conditions. Mines characterized by frequent changes in active workings, extensive diesel equipment fleets, and well-developed communication infrastructure are particularly suitable for the implementation of VFD and VoD technologies. Conversely, operations relying on aging infrastructure, unreliable communication systems, or facing significant gas-related hazards may require a gradual implementation strategy beginning with improved monitoring of airflow, gas concentrations, and fan performance.

Reported energy-saving values cannot be directly compared because they originate from different validation environments. Some results are based on measurements obtained in operating mines, whereas others are derived from laboratory experiments, numerical simulations, or optimization models. Consequently, studies supported by before-and-after field measurements provide the strongest evidence for practical implementation. Energy-efficiency objectives must never compromise ventilation safety. Minimum airflow quantities, acceptable air velocities, maximum permissible concentrations of hazardous gases, thermal comfort requirements, and emergency response procedures for fires or equipment failures must always take precedence over energy-saving targets. Therefore, modern ventilation systems should be capable of automatically reverting to a safe operating mode whenever sensors, communication systems, or automated control functions become unreliable.

7 CONCLUSION

The energy efficiency of underground mine ventilation systems can be improved through the reduction of network losses, the appropriate selection of fan operating modes, and the adjustment of airflow quantities to actual ventilation requirements. Variable Frequency Drive (VFD) control and Ventilation-on-Demand (VoD) systems offer the greatest practical potential, particularly when integrated with reliable monitoring systems and continuously updated ventilation network models.

CFD simulations, sensor-based monitoring systems, and predictive control models do not directly generate energy savings; however, they enable more reliable assessment of airflow distribution, gas dispersion, and the consequences of modifying ventilation operating conditions. Their practical value depends on the quality of input data and the validation of results through field measurements.

In mines with limitation of infrastructure, advanced ventilation management technologies should be implemented progressively. Initial efforts should focus on improving measurement systems, reducing air leakage, and optimizing auxiliary ventilation networks, after which VFD control and more sophisticated VoD solutions may be introduced. Throughout this process, personnel safety and the maintenance of stable underground atmospheric conditions must remain the primary aim governing any energy-optimization strategy.

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